The effect of ice damage and post-damage fertilization and competition control on understory microclimate of sugar maple (*Acer saccharum* Marsh.) stands

by William C. Parker[1]

The influence of ice damage, fertilization, and herbicide treatments on understory microclimate was examined in several sugar maple stands during three growing seasons. Stands with greater initial crown damage and lower leaf area index had higher understory light levels, elevated air temperatures and lower humidity. Ice damage had comparatively less effect on the below-ground environment. Stands with higher damage and lower leaf area index exhibited higher soil temperature and lower soil moisture availability in certain years. The strength and significance of the relationships of canopy features with microclimatic variables diminished over time with canopy recovery and growth of understory vegetation. Fertilization treatment effects on stand microclimate were not apparent, but competition control reduced understory leaf area, increased soil temperature, and had minimal influence on soil moisture status.

Key words: canopy, fertilization, ice storm, microclimate, natural disturbance, sugar maple, vegetation management

L'influence des dégâts du verglas, de la fertilisation et des traitements phytocides sur le microclimat en sous étage a été étudiée dans plusieurs érablières à sucre au cours de trois saisons de croissance. Les peuplements ayant des dégâts les plus importants au niveau de la cime et le plus faible indice de surface foliaire ont enregistré les plus hauts niveaux de luminosité pour le sous-étage, des températures supérieures de l'air et une humidité plus faible. Les dégâts du verglas ont eu comparativement moins d'effet sur l'environnement en sous-sol. Les peuplements ayant le plus haut niveau de dégâts et le plus faible indice de surface foliaire ont enregistré des températures plus élevées du sol et une plus faible disponibilité de l'humidité du sol certaines années. L'importance et la signification des relations entre les caractéristiques de la cime des arbres et les variables du microclimat ont diminué en fonction du temps avec la reconstruction de la cime des arbres et la croissance de la végétation en sous-étage. Les effets des traitements de fertilisation sur le microclimat des peuplements ne sont apparents, mais le contrôle de la compétition a réduit la surface foliaire du sous-étage, a augmenté la température du sol et a eu peu d'influence sur le niveau d'humidité du sol.

Mots-clés: cime des arbres, fertilisation, tempête de verglas, microclimat, perturbation naturelle, érable à sucre, gestion de la végétation

Introduction

Ice storms are a common, relatively frequent form of natural disturbance in forests of eastern North America (Lemon 1961; Irland 1998, 2000; Proulx and Greene 2001). On average, significant ice storm events occur once to several times per decade in the eastern United States and Canada (Irland 1998). Severe ice storms lasting several days and affecting large geographic areas are much less frequent, occurring once or twice every 100 years (Lemon 1961, Irland 2000). The ice storm that struck eastern Canada and the northeastern United States in January, 1998 was catastrophic in nature and affected 10 million ha (Irland 1998). In eastern Ontario, an unprecedented amount of freezing rain (70–110 mm) was deposited in some locations, causing damage to more than 600 000 ha of forest (Lautenschlager and Nielsen 1999). The maple syrup industry of Ontario is centred in this storm area and many syrup producing woodlots were severely damaged (Lautenschlager and Nielsen 1999).

Sudden natural and anthropogenic canopy disturbances result in immediate but transient changes in stand microclimate and resource availability (Bazzaz and Wayne 1994, Coates and Burton 1997, Aussenac 2000). The relative change in microclimate and time required for a return to pre-disturbance conditions are dependent on the severity of disturbance and rate of recovery of forest vegetation. Forest disturbance by ice storms results from excessive ice loading of tree crowns. Overstory canopy gaps of various sizes are formed by breaking of branches, bending of stems, and in extreme cases, snapping of main stems and uprooting of trees (Smith 2000, Proulx and Greene 2001). In addition to direct injury by ice loading, overstory trees in lower canopy positions and advance regeneration may suffer secondary mechanical damage by broken branches and other debris falling from the overstory (Bruederle and Stearns 1985, Boerner *et al.* 1988, Duguay *et al.* 2001).

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An integrated, interdisciplinary study was established in 1998 to investigate the immediate, short-, and long-term effects of ice damage on sap production, sap quality, and health of sugar maple stands (Lautenschlager and Nielsen 1999). This effort included experiments to determine the potential of fertilization and reduction of understory vegetation to enhance stand recovery and diminish the effects of damage on sap production, as well as to examine the ecological consequences of damage and treatments (Lautenschlager and Nielsen 1999). In this report, results are presented of a study that examined ice damage and remedial treatment effects on the microclimate of several sugar maple stands as influenced by initial damage levels and post-disturbance stand recovery.

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Table 1. Location, stand characteristics, crown damage estimates, and measurement schedule of sugar maple stands monitored for ice damage effects on understory microclimate. Region: (1) Limestone Plain, (2) Canadian Shield, (3) St. Lawrence River Valley, (4) Ottawa River Valley

Block	Region	Initial crown loss[1] (%)	Initial number of third-order branches[1]	Stand basal area (m^2)	DBH[1] (cm)	Height[1] (m)	Year after damage
3	2	41	9.0	17.2	32.1	23.0	1–3
5	1	10	19.4	20.8	40.1	22.7	1–3
9	1	61	18.3	19.0	53.7	22.3	1–3
11	2	61	10.8	25.2	41.3	24.6	1
12	4	64	8.3	28.0	43.3	23.0	1–3
14	2	71	11.7	19.2	37.9	23.3	2–3
15	1	37	21.7	16.4	43.5	19.5	1–3
19	2	10	21.1	20.0	45.5	23.6	1–3
29	4	35	14.5	20.0	57.5	25.4	1–3
31	3	6	18.3	23.8	34.5	24.5	1–3
42[2]	4	57	8.2	17.0	46.9	21.3	2–3
43[2]	4	40	11.0	18.1	27.9	17.4	2–3

[1]Values reported are block means of 24 focus trees.
[2]Herbicide demonstration blocks.

Materials and Methods

Study and treatment description

In November 1998, a 1-ha (100 m × 100 m) study block was established in 35 sugar maple stands representing a range of damage levels and physiographic regions (Lautenschlager and Nielsen 1999). Crown damage was assessed and each stand classified as receiving light (<20% crown loss), moderate (21–50% crown loss) or severe (>51% crown loss) damage (Lautenschlager and Nielsen 1999, Lautenschlager and Winters 2001). Each block contained 50 to 100 mature sugar maple trees with dbh ranging from 25–60 cm. These blocks were divided into 4, 50 m × 50-m treatment plots. In summer, 1999, plots in each block were randomly assigned one of four fertilization treatments: (1) P and K (each at 200 kg ha^{-1}), (2) dolomitic lime (55.5% $CaCO_3$, 42.5% $MgCO_3$) at 2000 kg ha^{-1} (3) P and K plus dolomitic lime, and (4) no treatment. In summer 1999, study blocks were established in three additional ice-damaged sugar maple stands to examine the effects of understory vegetation control on fertilization treatments to accelerate recovery of sugar maple trees. In these blocks, treatments consisted of: (1) a control (no treatment), (2) herbicide application (Vision® (3% aqueous glyphosate solution, 10.L ha^{-1})), (3) P and K plus dolomitic lime as described above, and (4) herbicide plus this fertilizer combination. Herbicide treatments were applied June 11–12, 1999 with a backpack mist-blower.

Microclimate measurements

Understory microclimate was monitored in 9 (1999) or 11 (2000–2001) of 35 blocks (Table 1). Data loggers (CR10X or CR10, Campbell-Scientific, Edmonton, AB) fitted with AM416 Relay Multiplexers (Campbell-Scientific, Edmonton, AB) and a variety of microenvironmental sensors were installed on each block and operated from April until early October. Light intensity at ~ 1 m (photosynthetic photon flux density (PPFD): 400–700 nm wavelength (μmol m^{-2} s^{-1})) was measured using a LI-190SB quantum sensor (LiCor Inc., Lincoln, NE) placed at one location in two treatment plots (15 and 47 m from block centre). Hourly mean PPFD values were used to estimate total daily PPFD (mol m^{-2}) received. Air temperature (Ta) and relative humidity (RH) at ~ 1 m were measured in one understory location 15 m from block centre. The Ta/RH sensor (CS500, Campbell-Scientific, Edmonton, AB) was housed in a 5-gilled radiation shield (Model 41301, Campbell-Scientific, Edmonton, AB). A seasonal Ta heat sum, growing degree days (GDD), was calculated for each instrumented block as daily mean Ta–5°C summed over the growing season. Midday vapour pressure deficit (VPD) was estimated by the mean of hourly VPD values from 10:00 AM to 3:00 PM.

Within each the 0.25-ha treatment plots, soil water potential (SWP) was measured using gypsum block sensors (Watermark 253, Campbell-Scientific, Edmonton, AB) placed at a depth of 5 cm in the mineral soil at 31 and 46 m from block centre. Soil water potential is defined in units of negative pressure, with wetter soils having higher (i.e., less negative) values of SWP. Daily SWP at each of these eight locations was estimated from a single measurement taken at 10:00 AM. Seasonal soil moisture availability was also defined in terms of percent "stress days" that occurred, the proportion of the growing season that mean daily SWP values were ≤ –0.2 MPa. At this SWP, the soil moisture content of these loamy soils is likely < 40% and many physiological processes are inhibited (Kramer and Boyer 1995).

Soil temperature at the location of soil moisture sensors was measured using probes constructed from 24 gauge, Cu-Ni (type T) thermocouple wire. A soil heat sum was calculated as daily mean Ts-5°C summed over the growing season. Daily rainfall received in eight of the 11 stands was measured with a tipping bucket rain gauge (TE525M, Texas Electronics, Inc., Dallas TX) placed in a canopy gap. Rainfall received in three stands was obtained from the nearest Environment Canada or Ontario Ministry of Natural Resources climate station.

Canopy measurements

Canopy features and the degree of ice damage to overstory and understory vegetation were determined by several methods. Percent overstory canopy cover and percent total (overstory and understory) canopy cover were estimated using digital photographs taken in August 1999 and 2001. One to three photographs were taken at 1 m above ground in each treatment plot, and a single photograph taken at block centre. Where an understory canopy (i.e., > 1-m height) was present, photographs were taken in locations with and without understory interference. Digital images were processed using Image-Pro Plus v3.0 software (Media Cybernetics, Inc., Silver Spring, MD) to estimate average percent canopy cover.

Leaf area index (one-sided) (LAI) and the canopy gap fraction were measured for each treatment plot within several study blocks each year using a TRAC, a hand-held optical instrument (3rd Wave Engineering, Nepean, ON). This instrument provides indirect estimates of LAI from measurements of light transmitted through plant canopies. As with other non-destructive approaches, the indirect LAI estimates provided by the TRAC may underestimate the true LAI, and are often referred to as "effective LAI." However, this instrument has been found to provide reliable estimates of LAI comparable in accuracy to other commonly used methods and instruments (Olthoff *et al.* 2001). The instrument was held ~ 1.5 m above the forest floor during its operation and therefore provides LAI and gap fraction values for the overstory and that portion of the understory canopy ≥ 1.5 m height. A more complete presentation of the methods used for TRAC measurements in this study is outlined in Olthoff *et al.* (2001).

Initial canopy damage was quantified by two separate ocular measures. Ground-based visual estimates of percent canopy damage (i.e., percent crown loss) for 24 focus trees per block (i.e., six trees per treatment plot) were obtained in 1999 and 2000 (Lautenschlager and Winters 2001). Damage classes were assigned to each block based on average percent crown loss of focus trees. In spring 2000 before leaf-out, the number of third-order branches (≥ 5 cm diameter) supported by focus trees was counted. These branch counts were strongly correlated with the total foliar biomass of individual maple trees (Lautenschlager and Winters 2001, Ter-Mikaelian and Lautenschlager 2001).

Understory vegetation was sampled in 1999 and 2001 using the line intercept method (Lautenschlager *et al.* 2003). In 1999, five, 10-m lines were randomly established in the central 25 m × 25 m of each treatment quadrant. Percent cover of vegetation along these lines was identified by plant functional type and height stratum (<0.5 m, 0.5 m–2 m, and 2–7 m). This survey method was expanded to 20, randomly established 5-m lines and understory vegetation re-measured in 2001.

Statistical analysis

Preliminary examination of fertilization effects revealed no consistent trends on below-ground microclimate. This is likely associated with the lack of nutrient amendment effects on stand LAI and percent cover of understory vegetation exhibited during the study period (Lautenschlager *et al.* 2003, Olthoff *et al.* 2003). As a result, fertilization treatment effects were not formally tested. Instead, analysis of variance was used to quantify the effects of damage class and time after disturbance on several microclimatic variables, using the mixed general linear model

$$Y_{ijkl} = u + D_i + B_{(i)j} + T_k + DT_{ik} + BT_{(ij)k} + E_{(ijk)l},$$

where D is damage class, B is block within damage class, and T is time (i.e., year). Only microclimatic variables measured at more than one location per block were included in this analysis (SWP, stress days, mean, maximum, and minimum daily Ts, and total PPFD). Seasonal mean values of these variables from individual sensors provided the observations used in analysis. This mixed model accounted for >70% of the variation in all dependent variables examined. A least significant difference test was used for multiple mean comparisons when main treatment effects were significant ($p \leq 0.05$). A non-parametric method was used for analysis of treatment effects on percent stress days because observations were not normally distributed. Data were converted to ranks and analysis of variance used to determine treatment effects. A Student-Newman-Kuels test was used for mean comparisons.

Herbicide treatment effects could only be assessed for below-ground microclimatic variables because above-ground sensors were not established in each treatment plot. Two-way analysis of variance and the general linear model,

$$Y_{ijk} = u + C_i + T_j + CT_{ij} + E_{ijk}$$

were used to quantify the effects of competition control treatment (C) and time (T) (i.e., day) on seasonal mean Ts and SWP for each block. Non-parametric methods and a Student-Newman-Kuels test were used to quantify competition control treatment effects on stress days for each block and year as described earlier.

The relationship of ice damage with seasonal mean values for microclimatic variables was also examined using correlation analysis and Pearson product moment correlation coefficients. Canopy features used in this analysis were gap fraction, LAI, percent overstory canopy cover, and percent cover of understory vegetation. Initial canopy damage as estimated by percent crown loss (average of 1999 and 2000 values) and third-order branch counts was also used in correlation analysis. For microclimate variables measured in more than one treatment plot (i.e., PPFD, Ts, and SWP), correlation analysis was performed using plot-based values. Mean block level values of canopy variables were used in correlation analysis with Ta and VPD, atmospheric variables for which we had only one sensor per block. The period June 9 to September 17 was defined as the growing season for each block and year to avoid phenological effects on microclimate.

Results

The growing season climate of southeastern Ontario was quite different among study years. The average total rainfall received by the study blocks in the 1999 growing season was slightly less (–7%) than the long-term climatic average of 393 mm. Mean June and July air temperature in 1999 were about 1.5°C higher than normal. The growing season of 2000 was relatively cool and wet, with above normal rainfall (+15%) and below average monthly air temperatures. A prolonged drought occurred in the growing season of 2001 with total rainfall being 38% below normal. Less than half the monthly average rainfall was received in July and August, and mean August and September air temperatures were about 2.5°C above normal. The late summer period of comparatively high air temperatures and little rainfall resulted in premature leaf abscission of deciduous tree species in many regions of southern Ontario (Olthoff *et al.* 2003).

Understory microclimate did not vary with damage class, but growing season had a significant effect on all variables tested except total PPFD (Table 2). Microclimate was strongly influenced by block within damage class, a treatment effect that differed significantly among growing seasons. The damage by time treatment interaction term was not significant, indicating the response of microclimate to damage class did not differ among growing seasons. The distinctly different air temperature and precipitation regimes of the three growing seasons were associated with significant differences in SWP, stress days, and Ts among study years (Table 3).

Table 2. Results of analysis of variance and the F test statistic for treatment effects on seasonal mean values of daily photosynthetic photon flux density (PPFD), soil water potential (SWP), percent stress days, and mean, minimum, and maximum daily soil temperature (Ts)[1]

Treatment	PPFD	SWP	Stress days	Mean Ts	Minimum Ts	Maximum Ts
Damage (D)	Ns	Ns	Ns	Ns	Ns	Ns
Time (T)	7.02***	33.60***	36.01***	93.15***	197.01***	107.48***
Block (B)	6.56**	Ns	2.96*	9.11***	3.87*	11.51***
D*T	Ns	Ns	Ns	Ns	Ns	Ns
B*T	Ns	4.56***	4.29***	2.51**	3.99***	Ns

[1]Asterisks following F values denote Pr > F: $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***), not significant (Ns). F values are not presented for non-significant treatment effects.

Table 3. Results of mean comparison tests of the effect of (a) damage class and (b) growing season on seasonal mean values of daily photon flux density (PPFD), soil water potential (SWP), percent stress days, and mean, minimum, and maximum daily soil temperature (Ts)[1]

Treatment	PPFD (mmol m^{-2})	SWP (MPa)	Stress days (%)	Mean Ts (°C)	Minimum Ts (°C)	Maximum Ts (°C)
(a) Damage						
Light	1.33a	–0.065a	7.3a	16.8a	10.8a	21.1a
Moderate	3.33a	–0.074a	8.0a	16.8a	11.2a	21.1a
Severe	4.55a	–0.071a	8.5a	16.7a	10.7a	21.2a
(b) Year						
1999	3.77a	–0.070b	5.8b	17.6a	11.4b	22.1a
2000	3.24a	–0.023a	0.2c	15.8c	8.6c	19.6c
2001	2.71a	–0.118c	17.7a	16.9b	12.6a	21.7b

[1]Means followed by the same letter are not significantly different ($p < 0.05$).

Pre-disturbance measures of canopy characteristics were not available for the maple stands used in this study. However, post-storm measurements of canopy features were strongly correlated with initial crown damage estimates in all three growing seasons (Table 4). These results and those of Olthoff *et al.* (2001) suggest that single-date measures of post-disturbance LAI, gap fraction and percent overstory canopy cover provided fairly reliable estimates of residual ice damage and canopy recovery in a given growing season.

Understory microclimate was primarily affected by overstory canopy characteristics, since above- and below-ground variables were independent of total understory cover and percent understory cover within individual stratum in any growing season (data not shown). Canopy features and initial overstory damage were significantly correlated with mean daily PPFD in each growing season, with more heavily damaged stands having higher understory light levels (Table 5). A significant negative exponential relationship existed between LAI and mean daily PPFD for data pooled over all three growing seasons (Fig. 1). Stand LAI accounted for more than 70% of the variation in mean daily PPFD observed, suggesting that season-averaged sky conditions did not differ greatly among the geographically separated blocks in a given year.

The influence of initial damage and canopy features on understory light levels was strongly correlated with air temperature and humidity regimes observed, with the presence and strength of these relationships varying by year (Table 5, Fig. 2). Higher maximum daily Ta, diurnal Ta range, and midday VPD were exhibited in stands with more open overstory canopies. Stands with higher LAI also showed a trend toward lower minimum daily Ta in 2000 ($r = 0.65$, $p < 0.08$) with a significant linear relationship observed between mean daily PPFD and minimum daily Ta in 2000 (Fig. 2). Growing degree day estimates were not related to canopy characteristics in any growing season, since ice damage and post-disturbance canopy features did not effect mean daily Ta.

Table 4. Results of correlation analysis of initial ice storm damage estimates with single-date measures of leaf area index (LAI), gap fraction, and percent overstory canopy cover[1]

		Initial damage estimate	
Canopy feature	Year	Crown loss (%)	Number third-order branches
LAI	1999	–0.512 **	0.734 **
	2000	–0.701 **	0.660 **
	2001	Ns	0.487 **
Gap fraction	1999	0.480 *	–0.671 **
	2000	0.657 **	–0.625 **
	2001	0.668 **	–0.682 **
Overstory cover (%)	1999	–0.573 **	0.550 **
	2001	–0.529 **	0.522 **

[1]Correlation coefficients and probability levels are presented for significant relationships: $p < 0.05$ (*), $p < 0.01$ (**) and not significant (Ns). Analysis was performed using plot-based mean values of damage and canopy features. Percent overstory canopy cover data were not collected in 2000.

Similar damage and canopy effects on seasonal trends in Ts were observed in the second season following the ice storm (1999) but not thereafter. Higher average daily mean, maximum, and minimum Ts were exhibited in stands with greater initial canopy damage, lower LAI (Table 6) and higher mean daily PPFD (Fig. 3). The diurnal range in Ts was also larger in stands with more open canopies, likely due to a greater comparative increase in maximum than minimum daily Ts. A significant negative relationship was also exhibited between the seasonal soil heat sum and several canopy features in 1999, a reflection of higher mean daily PPFD and mean daily Ts in more open stands (Table 6).

Seasonal soil moisture availability as measured by mean SWP and percent stress days was not related to total rainfall received in any growing season (Table 7). However, these two variables

Table 5. Results of correlation analysis of mean canopy characteristics with seasonal mean values of total daily photosynthetic photon flux density (PPFD), mean, maximum, and minimum daily air temperature (Ta), mean daily range in Ta, and mean daily midday vapour pressure deficit (VPD) in three growing seasons[1]

Microclimate	Year	Stand LAI	Gap fraction	Overstory canopy cover (%)	Initial crown loss (%)	Initial number of third-order branches
PPFD	1999	–0.759 **	0.907 **	–0.794 **	0.543 *	–0.605 **
	2000	–0.869 **	0.874 *	–	0.641 **	Ns
	2001	–0.572 *	Ns	Ns	0.451 *	Ns
Mean Ta	1999	Ns	Ns	Ns	Ns	Ns
	2000	Ns	Ns	–	Ns	Ns
	2001	Ns	Ns	Ns	Ns	Ns
Maximum Ta	1999	Ns	Ns	–0.833 **	Ns	Ns
	2000	–0.870 **	0.898 **	–	Ns	Ns
	2001	Ns	0.932 **	–0.838 **	Ns	Ns
Minimum Ta	1999	Ns	Ns	Ns	Ns	Ns
	2000	Ns	Ns	–	Ns	Ns
	2001	Ns	Ns	Ns	Ns	Ns
Diurnal Ta range	1999	Ns	Ns	–0.762 *	Ns	Ns
	2000	–0.859 **	0.891 **	–	0.634 *	Ns
	2001	Ns	0.708 *	–0.769 **	Ns	Ns
Midday VPD	1999	Ns	Ns	–0.700 *	0.696 *	Ns
	2000	–0.829 **	0.725 *	–	0.607 *	Ns
	2001	Ns	0.700 *	–0.653 *	0.712 *	Ns

[1]Correlation coefficients and probability levels are presented for significant relationships: $p < 0.05$ (*), $p < 0.01$ (**) and not significant (Ns). Percent overstory canopy cover data were not collected in 2000.

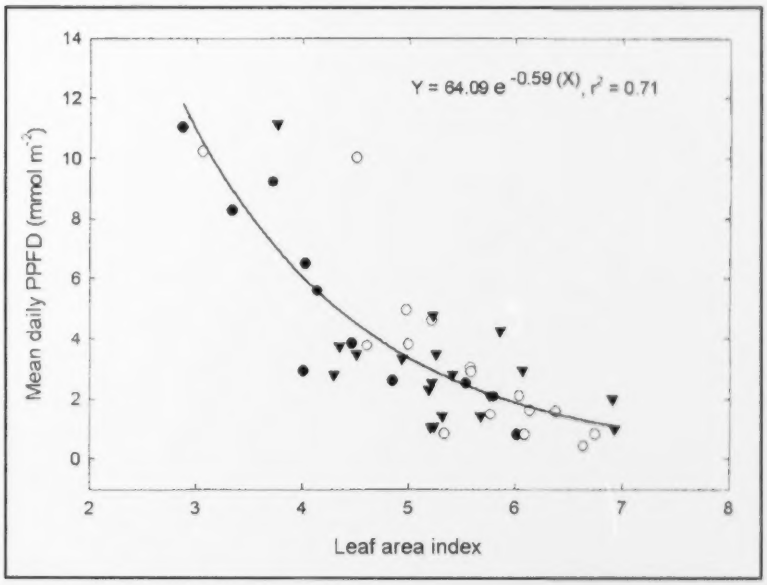

Fig. 1. The relationship of total stand leaf area index with mean daily PPFD for the 1999 (solid circles), 2000 (open circles) and 2001 (triangles) growing seasons. The regression equation and coefficient of determination (r^2) are presented. Each observation represents a plot mean value.

were sometimes significantly related to initial damage and post-disturbance canopy features. These results indicate that in both abnormally wet and dry growing seasons, stands with less canopy damage tended to have a higher moisture content in the upper soil layer.

Competition control treatment had a substantial influence on stand structure. Herbicide application reduced stand LAI by 15–20% and percent cover of understory vegetation by about 45–60%, with larger comparative reductions occurring in block 43 (Table 8). Decreased stand LAI resulted from the removal of woody understory vegetation greater than 1.5 m in height. The competition control treatment was associated with significantly higher daily mean, maximum and minimum Ts, and a greater diurnal Ts range, although this response varied slightly between blocks and growing seasons (Table 8). Understory removal had a significant effect on seasonal soil moisture availability only

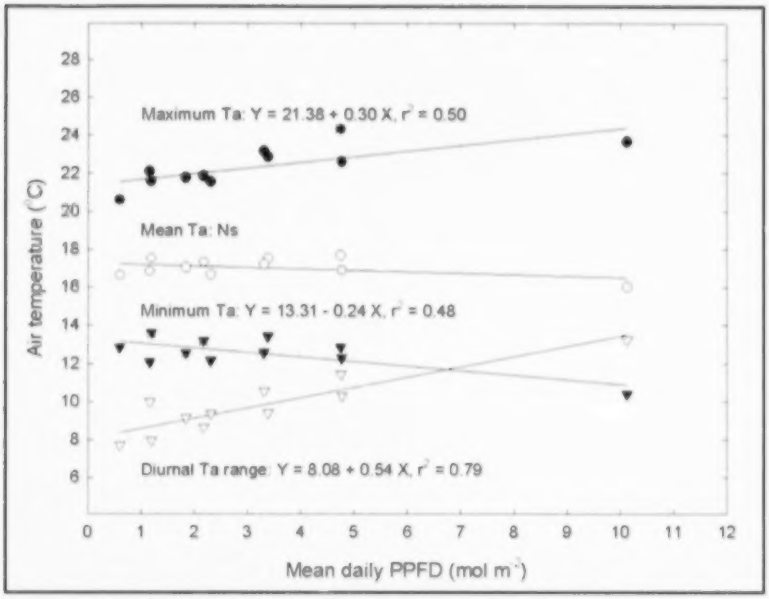
Maximum Ta: Y = 21.38 + 0.30 X, r² = 0.50
Mean Ta: Ns
Minimum Ta: Y = 13.31 - 0.24 X, r² = 0.48
Diurnal Ta range: Y = 8.08 + 0.54 X, r² = 0.79
Air temperature (°C)
Mean daily PPFD (mol m⁻²)

Fig. 2. The relationship of seasonal mean values for mean, maximum, and minimum daily air temperature (Ta), and the diurnal Ta range with mean daily PPFD in the 2000 growing season. Each observation represents a single Ta measurement and the mean of two PPFD values per block. Linear regression equations and coefficients of determination (r^2) are presented for significant ($p \leq 0.05$) relationships. Lack of a significant linear relationship between the dependent and independent variable is denoted as Ns.

Table 6. Results of correlation analysis of canopy characteristics with seasonal mean values for mean, maximum, and minimum daily soil temperature, and mean diurnal range in soil temperature in three growing seasons[1]

Microclimate	Year	Stand LAI	Gap fraction	Overstory canopy cover (%)	Initial crown loss (%)	Initial number of third-order branches
Mean Ts	1999	–0.677 **	0.765 **	–0.471 **	Ns	–0.576 **
	2000	Ns	Ns	–	Ns	Ns
	2001	Ns	Ns	Ns	Ns	Ns
Maximum Ts	1999	–0.710 **	0.826 **	–0.557 **	0.383 *	–0.628 **
	2000	Ns	Ns	–	Ns	Ns
	2001	Ns	Ns	–0.386 *	Ns	Ns
Minimum Ts	1999	–0.580 **	0.634 **	Ns	Ns	–0.425 **
	2000	Ns	Ns	–	Ns	Ns
	2001	Ns	Ns	Ns	–0.321 *	Ns
Diurnal Ts range	1999	–0.632 **	0.779 **	–0.616 **	0.679 **	–0.574 **
	2000	Ns	Ns	–	0.474 **	–0.317 *
	2001	Ns	Ns	–0.528 **	0.382 *	Ns
Soil heat sum	1999	–0.701 **	0.762 **	–0.469 **	Ns	–0.585 **
	2000	Ns	Ns	–	Ns	Ns
	2001	Ns	Ns	Ns	Ns	–0.340 *

[1]Correlation coefficients and probability levels are presented for significant relationships: $p < 0.05$ (*), $p < 0.01$ (**) and not significant (Ns). Percent overstory canopy cover data were not collected in 2000.

in block 43 in the 2000 growing season when herbicide treated plots had a higher mean SWP (Table 8).

Discussion

Microclimate of ice damaged sugar maple stands differed significantly among growing seasons and study blocks, but not with damage class. Differences in climate, stand and site factors among the geographically disjunct study blocks likely diminished the ability to detect damage class effects on microclimate. The significant effect of time on several microclimate variables is a function of both climatic variation among growing seasons and the degree of recovery in overstory and understory vegetation that occurred over the study period. However, the variation in soil moisture and soil temperature exhibited among growing seasons is most likely due to climatic factors and the relatively large differences in temperature and rainfall patterns that occurred over the study period.

Ice damage to the overstory canopy of sugar maple stands in our study influenced microclimate primarily through changes in stand net radiation balance. Increased understory PPFD likely contributed to the post-disturbance increase in understory vegetative cover observed (Lautenschlager *et al.* 2003, Olthoff *et al.* 2003). Higher daytime radiation received in the understory of maple stands suffering greater canopy damage was associated with higher maximum daily Ta, a greater diurnal Ta range, and higher midday VPD. Trends toward lower minimum

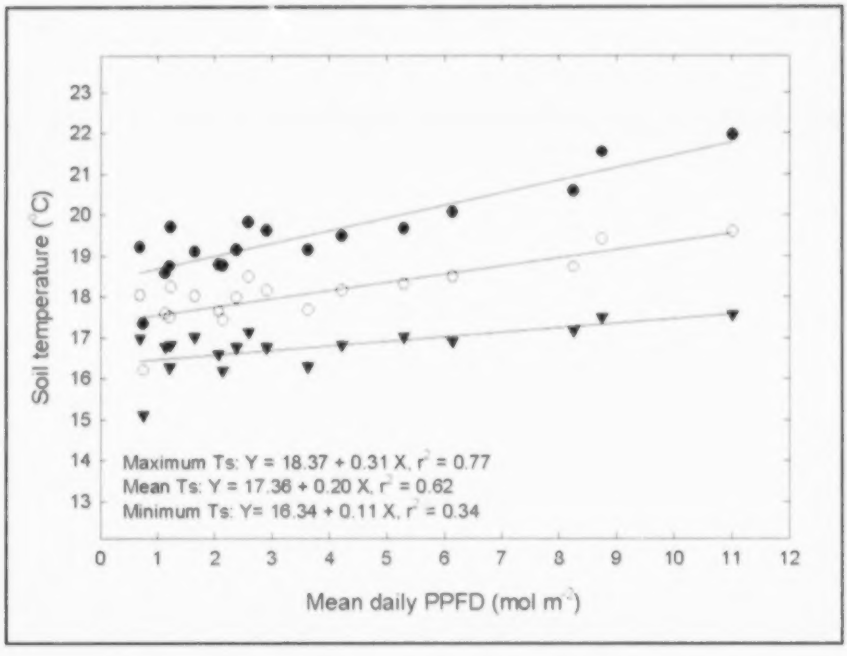
Soil temperature (°C)
Mean daily PPFD (mol m⁻²)
Maximum Ts: Y = 18.37 + 0.31 X, r² = 0.77
Mean Ts: Y = 17.36 + 0.20 X, r² = 0.62
Minimum Ts: Y= 16.34 + 0.11 X, r² = 0.34

Fig. 3. The relationship of seasonal mean values of mean (open circles), maximum (solid circles), and minimum (triangles) daily soil temperature with mean daily PPFD in the 1999 growing season. Each observation represents the mean of two soil temperature sensors and a single PPFD value for two treatment plots per block. Linear regression equations and coefficients of determination (r^2) are presented for significant ($p \leq 0.05$) relationships.

Table 7. Results of correlation analysis of seasonal soil moisture availability with stand features for three study years

	1999		2000		2001	
	Mean SWP (MPa)	Stress days (%)	Mean SWP (MPa)	Stress days (%)	Mean SWP (MPa)	Stress days (%)
LAI	Ns	Ns	–0.393 *	Ns	Ns	Ns
Gap fraction	Ns	Ns	Ns	Ns	0.394 *	Ns
Overstory cover (%)	Ns	Ns	–	–	Ns	Ns
Third-order branches (#)	Ns	Ns	–0.537 **	Ns	–0.413 **	–0.354 *
Initial crown loss (%)	Ns	Ns	0.356 *	Ns	Ns	Ns
Rainfall	Ns	Ns	Ns	Ns	Ns	Ns

[1]Correlation coefficients and probability levels are reported for significant relationships: $p < 0.05$ (*), $p < 0.01$ (**), and not significant (Ns). Plot level canopy values and the mean of two soil moisture sensors for each treatment plot in a study block were used in analysis (n =32–48). Correlation between soil moisture availability and rainfall performed with block means (n = 9–11). Percent overstory and understory cover were not collected in 2000.

daily Ta were likely associated with enhanced longwave radiation emission of the ground surface to the atmosphere at night. While conclusions regarding damage effects on understory Ta are hampered by use of a single temperature sensor, the trend toward lower minimum daily Ta suggests a higher likelihood of late spring frost in more heavily damaged maple stands (Hungerford and Babbit 1987, Grossnickle *et al.* 2001).

Forest soil temperature regime is also closely related to canopy density as well as the thickness and thermal properties of the forest floor (Hungerford and Babbit 1987, Stathers and Spittlehouse 1990, Aussenac 2000). Similar to patterns observed for understory Ta, stands that suffered greater ice damage exhibited higher mean and maximum Ts. However, elevated minimum Ts in stands with greater canopy damage suggests the upper soil layers were buffered from enhanced radiational cooling at night by ground vegetation (<0.5 m height) and the forest floor surface organic layers (Stathers and Spittlehouse 1990).

Ice damage effects on microclimate tended to decrease with time, probably the result of increases in stand leaf area and closure of canopy gaps that occurs following ice storms and other types of canopy disturbance (Spaulding and Bratton 1946, De Steven *et al.* 1991, Runkle 1998, Olthoff *et al.* 2003). Mean total stand LAI of ice-damaged sugar maple stands increased from 4.54 to 5.52 over the three-year study period (Olthoff *et al.* 2003). Leaf area index of the 2–7 m layer of understory vegetation increased by almost 300% during this period, and accounted for about 45% of the change in total LAI observed (Olthoff *et al.* 2003). Post-disturbance recovery of the overstory and understory canopy likely reduced radiation exchange between the ground surface and the atmosphere and diminished the differences in mean daily PPFD, Ta, etc. initially observed among stands with different damage levels (Stathers and Spittlehouse 1990, Grossnickle *et al.* 2001).

Increased soil moisture following canopy disturbances that result in substantial reductions in leaf area may occur due to decreased stand-level transpiration and/or lower canopy interception of rainfall (Cregg *et al.* 1990, Bréda *et al.* 1995, Aussenac 2000). In my study, moisture availability in the upper soil layer tended to be higher in stands with less initial damage and higher LAI in two of three growing seasons. However, the inherent limitations of measuring soil water content in terms of soil water potential using gypsum block sensors placed at a single depth must temper any conclusions regard-

Table 8. The effect of competition control treatment effects on mean seasonal values of mean, maximum, and minimum daily soil temperature (Ts), daily Ts range, daily soil water potential (SWP), percent stress days, stand LAI and total understory percent cover in block 42 and 43 during the 2000 and 2001 growing seasons[1]

		Block 42		Block 43	
	Year	Herbicide	Control	Herbicide	Control
Mean Ts	2000	16.8a	15.8b	16.2a	15.7b
	2001	17.7a	17.4b	17.7a	17.0b
Maximum Ts	2000	18.5a	17.1b	17.7a	16.7b
	2001	19.2a	18.9b	19.1a	17.9b
Minimum Ts	2000	15.2a	14.6b	14.9a	14.8a
	2001	16.4a	16.1b	16.2a	16.2a
Daily Ts range	2000	3.3a	2.5b	2.8a	1.9b
	2001	2.8a	2.7a	2.9a	1.7b
SWP (MPa)	2000	–0.059a	–0.062a	–0.058a	–0.078b
	2001	–0.146a	–0.143a	–0.197a	–0.197a
Stress days (%)	2000	0a	0a	8.7a	13.1a
	2001	26.5a	25.0a	37.1a	40.8a
Stand LAI	2000	4.39	5.16	4.42	5.63
	2001	5.00	5.50	4.08	5.62
Total cover (%)	2001	110.1	207.3	76.2	182.6

[1]Means followed by the same letter within a given year and block are not significantly different ($p \leq 0.05$). Leaf area index and total percent understory cover values are the mean of two treatment plot values.

ing apparent damage effects on seasonal soil moisture availability. Assuming these measurements provide a reliable indicator of soil moisture status, the trend toward reduced mean SWP and percent stress days may be related to enhanced transpiration in more heavily damaged stands. Our findings of increased mean daily PPFD, Ta, and midday VPD in stands with greater damage and lower LAI suggest the overstory canopies of these stands were exposed to atmospheric conditions conducive to relatively high rates of tree and stand transpiration (Oren *et al.* 1999, Oren and Pataki 2001). Similar findings have been reported after thinning, with higher within-canopy PPFD, Ta, and VPD resulting in increased stand transpiration, despite reductions in stand density and stand leaf area (Bréda *et al.* 1995, Tang *et al.* 1999, Aussenac 2000).

Liming and fertilization did not stimulate leaf area recovery of ice-damaged sugar maple stands (Lautenschlager *et al.* 2003, Olthoff *et al.* 2003) and no clear trends in microclimate with fertilization treatment were observed. By comparison, competition control had a significant effect on stand LAI, abundance of understory vegetation, and microclimate. Shading of the forest floor by overstory and understory vegetation strongly modifies the soil thermal regime (van Wijk 1965, Oliver *et al.* 1987, Spittlehouse and Stathers 1990). Partial reduction in understory forest cover by herbicide treatment was associated with slight but significant increases in Ts, likely due to the comparatively small influence of the understory canopy on soil microclimate relative to the overstory. Although herbicide effects on Ts were not particularly large, decreased understory cover probably increased canopy transmittance of radiation and warming of the forest floor and upper soil layer (Oliver *et al.* 1987, Spittlehouse and Stathers 1990).

Control of understory vegetation has resulted in positive growth responses of overstory trees, presumably due to reduced root competition and increased soil moisture content (Johnson and Kovner 1956, Barrett and Youngberg 1965, Walters 1978, Harrington and Edwards 1999). This response is most fully expressed in stands where seasonal soil moisture availability is a growth-limiting factor and where the understory contributes a significant proportion of total stand transpiration (Tan and Black 1976, Kelliher *et al.* 1990). A significant increase in soil moisture was observed in one herbicide-treated block, but only in a year of above-average rainfall. This result suggests that root competition for soil moisture between overstory and understory vegetation in these two stands was minimal, and understory transpiration of these relatively dense stands (LAI > 4.1) was small relative to that of the overstory canopy.

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